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Art. VIII.—*The Petrology of the Ordovician Sediments of the Bendigo District.*

By J. A. DUNN, B.Sc.
(Howitt Natural History Research Scholar, 1920).

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1. Introduction.

The Ordovician sediments form practically the only rocks actually represented in Bendigo, and outcrop over almost the whole area except where occasionally covered by shallow alluvium. The structure of the series has been so thoroughly described by numerous geological workers in the past, particularly E. J. Dunn[1] and F. L. Stillwell,[2] that no description is here needed. One or two points may however be noted.

An exhaustive examination of the graptolites obtained from different parts of the field has shown that the Lancefield, Bendigo and Castlemaine zones of the Lower Ordovician are represented here, but there is, however, no lithological difference in the representatives of these three zones. There is every gradation between a typical sandstone and a typical slate, and these are the only representatives of the original sediments. The fresh slate has a dark to light bluish-grey colour, the sandstone a dark to light grey shade. On weathering this is altered to a buff colour in both cases, the slates being generally darker than the sandstone, except where the latter have been almost entirely replaced by limonite. The limonite staining is derived from the decomposition by meteoric waters of the pyrite contained in the fresh rock, and replaces the clayey material, and constitutes the more important cement of the weathered rock. Where, however, the importance of the limonite as a cementing medium is small, the sandstone becomes a soft, porous, crumbly sandstone, and the slate a fine greasy fissile material.

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[2] "Report on the Bendigo Goldfield," Nos 1 and 2. E. J. Dunn, Geol. Surv. Vict. 1896.

[2] "Gold Deposition in the Bendigo Goldfield," Parts I., II., and III. F. L. Stillwell. Bull 4.8 and 16. Adv. Council Sc. and Industry.

2. Composition of the Sediments.

Secondary silica has, in many cases, altered the character of the original sediments, but it is quite apparent that as a whole both the sandstones and slates were highly aluminous. The principal minerals identified microscopically are quartz, felspar, muscovite, and biotite (generally altered to chlorite). The accessories detected are tourmaline, zircon, rutile, ilmenite (often altering to leucoxene), magnetite, apatite and sphene. A small pale-bluish isotropic mineral with very high refractive index was detected in one section of sandstone—this is probably blue spinel. Secondary minerals present are quartz, pyrite, arsenopyrite, sphalerite, galena, chlorite and a carbonate probably ankerite. Sericite constitutes practically the whole of the ground-mass of the slates, leucoxene often appears secondary to ilmenite, whilst chlorite generally occurs after biotite. In a number of the slates, particularly those found on the " backs," black carbonaceous matter constitutes an integral part of the rock, and generally occurs in thin lamellae.

(a) Essential Minerals examined in thin sections.—The detrital quartz and felspars range to about .7 mm. as a maximum in the standstones and mica often occurs in long, thin ragged plates up to 1 mm. in length.

The quartz is rounded to sub-angular in habit generally, but often where secondary it becomes sharply angular. Only in very rare instances does it show crystal boundaries. Strain polarisation is rarely evident except in some of the secondary quartz. The characteristic serial arrangement of inclusions is often noticeable, and apatite, zircon and rutile are occasionally found as inclusions. Thin veins of quartz often traverse both sandstones and slates—these veins are in part the result of replacement, and in part of growth by force of crystallisation.

The felspar is in much less quantity than the quartz, and on the whole the individual grains are smaller. Occasionally the felspars are in very turbid grey patches, but generally they are rather fresh and represented by both orthoclase and plagioclase. The plagioclase ranges from andesine to oligoclase as shown by the angle of extinction, and is not so abundant as the orthoclase. The felspars are almost universally rounded in habit, but where they are probably secondary, they become quite angular, as in the case of quartz. The alteration of the felspars is as a rule to sericite, but occasionally it goes to calcite.

Both detrital and secondary mica occurs, the former as long, ragged, cleaved fragments of muscovite up to 1 mm. in length, and as rounded and ragged plates. Although for the most part quite clear and colourless, it occasionally alters to a pale green chlorite. The muscovite is often found bent and nipped between the quartz grains, and this is characteristic of every section examined. Biotite occurs in one or two of the sandstones, but is practically all altered to a greenish and brownish chlorite.

The secondary mica is generally represented by sericite, occurring throughout the ground-mass of all the rocks, and making up practically the whole of the slates. The sericite constitutes most of the original clayey matter of the ground-mass of the sandstones, and at times is the result of alteration of the felspars. Some of the plates of muscovite may possibly be secondary.

(b) Accessory Minerals.—Tourmaline is the dominant accessory, and was detected in every section of sandstone. Both the blue and brown pleochroic varieties are represented in grains up to .2 mm. diameter. Generally it occurs as rounded detrital grains, but occasionally it shows traces of crystal boundaries. Only in one case was tourmaline found to occur in slate, and in that instance it was included in secondary arsenopyrite.

Zircon occurs in all of the sections, never exceeding more than .25 mm. diameter. It is always clear and colourless, and generally slightly rounded, though still showing crystal boundaries. It is not so abundant in the slates as in the sandstones.

Rutile occurs in a number of the sections, but rarely exceeds more than .1 mm. diameter. Generally the grains are somewhat rounded, brown and violet pleochroic tints being common.

Apatite is a rather constant accessory in many of the sections in grains up to .3 mm. maximum. Although sometimes rounded, it always shows traces of crystal boundaries.

The determination of sphene in some of the sections is doubtful, owing to the difficulty of distinguishing it from zircon in small grains. But one or two boat-shaped crystals, with oblique extinction appear rather definite.

Ilmenite is quite a common accessory in all the rocks, occurring as irregular grains generally altering to leucoxene. Magnetite also occurs in irregular grains, rarely in minute octahedra.

Carbonaceous material occurs especially in the slates, and is probably the result of the decay of some form of life in the sediments during their deposition.

(c) Secondary Minerals.—Quartz is the chief secondary mineral. Practically all the Bendigo rocks are silicified to a greater or less extent. This secondary silica occurs either in the ground-mass, or at times it forms small angular grains of quartz which have grown from definite points by force of crystallisation; this often gives the appearance of a sandstone to what was originally a slate. At other times the quartz acts as a border to secondary cubes of pyrite, generally bordering the quartz only in the direction of the cleavage of the slates.

Chlorite is an important secondary mineral. In part this appears to have been brought in with the secondary siliceous solutions, but occasionally it is secondary to muscovite, biotite and tourmaline.

Mineral carbonates, probably ankerite, are common as secondary minerals, generally replacing the ground-mass of both slates and sandstones, and occasionally replacing grains of felspar. These carbonates also appear to have accompanied the secondary siliceous solutions.

Pyrite, pyrrhotite, arsenopyrite, sphalerite, and galena occur distributed throughout the whole series. They occur both irregularly, and with definite crystal boundaries, and are probably contemporaneous with the siliceous solutions.

Leucoxene is secondary after ilmenite. The greater part of the sericite is also secondary, particularly in the slates and ground-mass of the sandstones—it is evidently the alteration product of the clayey material of the original sediments.

Heavy Liquid Separation of Minerals.

By means of heavy liquids, the minerals occurring in small quantity in a sample of sandstone were isolated and examined as grains under the microscope. A typical sandstone from the 2400 feet level of the Sea Mine was crushed, then ground in a disc crusher, and passed first through an 80-mesh sieve, then part through a 100-mesh, thus giving two grades of fineness. These were then weighed:—

2817 grams through 100-mesh.
438 grams through 80 mesh, and over 100-mesh.

3255 grams total.

These grades were each panned off separately to ensure cleaner panning. Residues were panned three times to have a minimum loss of heavier minerals. By this means all slimes were got rid of, as well as a large proportion of the quartz. Concentrates dried, then passed under electro-magnet to separate any magnetic minerals. The magnetic minerals on examination consisted entirely of magnetite. This was also weighed:—

.9130 grams magnetite through 100-mesh.
.2889 grams magnetite through 80-mesh and over 100.
1.2019 grams magnetite total.

Magnetite in sandstone: .0307 per cent.

The demagnetised samples were each separated into a lighter and heavier portion, by means of flotation in bromoform S.G. 2.90, on the lines indicated by T. Crook, A.R.C.Sc. (Dublin), F.G.S., in "The Petrology of the Sedimentary Rocks," Hatch and Rastall. The concentrates obtained, i.e., the heavier portions, were weighed—

8.301 grams through 100-mesh.
3.756 grams between 80 and 100-mesh.
12.057 grams total concentrate.

These concentrates were seen to be heavily charged with sulphides, as pyrite and arsenopyrite. They were therefore first roasted to oxide, then again passed under electromagnet to eliminate pyritic matter, but a good deal of Fe_2O_3 still remained. Hence the only recourse left was to take it into solution with weak Hydrochloric acid, the leached residues being then filtered, dried and weighed—

2.7368 grams through 100-mesh.
0.4520 grams between 80 and 100-mesh.
3.1888 grams total.

Substracting this from the above 12.057 grams we find there was a total of 8.868 grams of sulphides in the sandstone, mainly pyrite.

Sulphide in sandstone—.2730 per cent.

The acid solution was tested for phosphate, as apatite appeared to be the only likely soluble mineral present. Presence of phosphate confirmed.

The filtered residues were noted to contain quite a large amount of quartz, hence a further heavy solution separation was undertaken. Bromoform being now unobtainable, methylene iodide, diluted to S.G. 3.133 was used for the purpose. This would also eliminate the large amount of muscovite which the rock sections had shown to be present. The final concentrates obtained were weighed:—

.0658 grams heavy minerals through 100-mesh.
.0091 grams heavy minerals between 80 and 100-mesh.

.0749 grams heavy minerals total.

Heavy minerals in sandstone—.0023 per cent.

The heavy minerals were then examined under the microscope in media of different refractive indices, the following minerals being detected: Zircon, tourmaline, ilmenite, rutile, topaz, sphene, magnetite, spinel, apatite, biotite, corundum, pyrrhotite, arsenopyrite, chalcopyrite, pyrite, gold; some quartz, chlorite, and muscovite, probably brought down with other minerals during flotation; and perhaps monazite.

Zircon is, with tourmaline, the most abundant. The crystals almost always show perfect prismatic and pyramidal faces, and in many cases are zoned.

Tourmaline occurs abundantly as both the brown and bluish varieties, generally in irregular grains, although a crystal face can be occasionally detected.

Ilmenite is generally altered to white leucoxene, showing in many cases a black, unaltered core.

Rutile occurs in well-formed prisms, sometimes dark brown in colour, sometimes violet tinted.

Topaz occurs generally in irregular grains, but occasionally shows prismatic outlines. The colours vary from colourless, through straw yellow to light greenish yellow.

Sphene is present in angular and rounded brown grains, generally not so clear as zircon and rutile. The determination is rather doubtful.

Pleonaste, an almost opaque form of spinel, was represented by two or three octahedra. Practically black, but greenish tint detected on edges.

Apatite showing rounded boundaries, owing to the leaching in HCl occurs in colorless and pale-bluish grains.

Corundum, or sapphire, occurs, but only three irregular grains noted, deep blue in colour, and rather pleochroic.

One or two round grains with very high refractive index and birefringence were noted, possessing a strong honey-yellow colour, are probably monazite, although the distinction from rutile is doubtful.

Pyrrhotite, arsenopyrite, chalcopyrite, pyrite and gold were detected. The first four were evidently unacted on by the acid for some reason. The gold occurs in two or three irregular grains, and is quite evidently not detrital. Even after the grinding which the gold would have received during crushing, it appears quite crystalline, while one grain is thin and skeleton-like, as if it had occurred in a mineral which had been dissolved by acid. This inclines the writer to the view that the gold was included in pyrite, and on solution of this latter, was left as the minute grains noted—the largest is not greater than .2 mm. diameter. It is a well-known fact that throughout Bendigo pyrite carries gold often in considerable quantities. It may be here noted that this gold could not have been included during crushing, sieving or panning, as the disc crusher was first thoroughly cleaned with pure silica, the sieves and pans also thoroughly cleaned. The writer is convinced the gold was inherent in the sample.

Magnetite was detected in minute grains, evidently having escaped separation by the electro-magnet by reason of its small size.

Ragged plates of deep brown biotite, colourless muscovite, and greenish chlorite were detected, and were probably brought down by some of the heavy minerals during flotation.

3. Structural Alterations and Metamorphism.

The structural alterations of the Bendigo rocks are wholly dynamic—the development of cleavage in the more argillaceous sediments with the production of slates. No shales or mudstones are represented, all having been converted into slates. As these become more arenaceous, however, the cleavage is less developed, until in the true sandstone there is no evidence of it whatever. These structural changes are certainly a result of the same intense forces that brought into existence the peculiar regular and acute folding so typical of the area. Although the Ordovician is intruded by numerous monchiquite dykes (generally in the neighbourhood of the anticlinal axes), there has been no alteration of the walls of country rock. This is probably accounted for by the almost instantaneous intrusion of the molten material, the magmatic heat being quickly conducted away from the walls.

Some eight miles south of Bendigo, at Big Hill, the Ordovician, at the contact with the Harcourt granitic mass, has been somewhat metamorphosed.[3] Typically the sandstones have been altered to a mica hornfels, and the argillaceous sediments to spotted and andalusite slates. For the most part, however, the alteration is rather an induration than an absolute change in the mineral content of the rocks.

4. Deposition of the Sediments.

By numerous writers in the past, some of the Ordovician beds of the Bendigo goldfields have been referred to as deposited in shallow water, owing to the common occurrence of ripple-marking.[4] It was first thought by Dr. Hall, and later confirmed by T. S. Hart[5] that the origin of these pseudo ripple markings is due to the intense compressive forces to which the rocks have been subjected. It appears probable that during the process of folding, the resultant stresses along the bedding planes caused movement of the beds over each other, with the concomitant production of minute puckers in the more plastic beds. This may be the explanation of the more common occurrence of this pseudo ripple-marking in the slates than in the sandstones of Bendigo. Hence, this evidence of apparent ripple-marking cannot be accepted as a criterion of the shallow-water deposition of the sediments.

The general fineness in grain of the rocks rather points to the deposition of the sediments some distance from the shore, probably in the relatively deep-water of a continental shelf. The often rapid succession of exceedingly minute bands of slate and sandstone, with the admixture of occasional quite coarse sandstones, suggests that the sediments were laid down under variable currents, probably a result of tremendous floods washing the material from various sources.

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[3] "Report on the Bendigo Goldfield," No. 1. E. J. Dunn, page 7.

[4] "Report on the Bendigo Goldfeld," No. 1. E. J. Dunn, page 6.

[5] "On some Features of the Ordovician Rocks at Daylesford, with a Comparison with Similar Occurrences elsewhere." T. S. Hart, M.A., B.C.E., Proc. Roy. Soc. Vic.. 1901, page 175.

5. Origin of the Mineral Contents.

W. G. Langford,[6] in his discussion of the constitution and origin of the Melbourne Silurian Sediments, pointed out that there were two possible sources of the material for the silurian sediments. So also there are two possible sources of the Ordovician sediments:—

(a) They may have been derived from a pre-Ordovician igneous rock.

(b) They may have been derived from a pre-Ordovician sedimentary rock.

The presence of such minerals as muscovite, tourmaline, zircon, rutile, ilmenite, magnetite, apatite, topaz, and sphene would perhaps point to an igneous rock as the origin of the sediments, but being stable minerals they may easily undergo transportation from the sediments of one period to a later.

Biotite is very rare, and is generally altered to chlorite, but its presence would indicate either an igneous or a metamorphic origin, as would also the fresh felspars which are occasionally met with. In the sandstones, felspar grains are very few in number compared with the quartz, and are sometimes represented by turbid patches. The slates and the fine sericitic ground-mass of the sandstones, however, are purely argillaceous, and must have originally been of the nature of clay, which in its turn, must have come into being through the prolonged breakdown of felspars. The extreme fineness of this clayey material would rather point to an older sediment as the derivation of the greater part of it. The clear unaltered felspars, though few in number, would tend to show that at least part of the constituent mineral content was derived from an old igneous or metamorphic rock.

The gradual transition from Heathcotian to Lower Ordovician throughout Victoria eliminates the possibility of the Heathcotian being the source of the material, whilst any possible Pre-Cambrian outcrops are quite unknown anywhere within 100 miles of Bendigo.

The writer pictures, then, in the Lower Ordovician period, a gradually sinking landmass, probably to the east, over which outcropped Pre-Cambrian metamorphic sediments, intruded perhaps by occasional igneous masses. The denudation of this land

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[6] "The Petrology of the Silurian Sediments near Melbourne." W. G. Langford, B.Sc., Proc. Roy. Soc. Vic., Vol. XXIX., n.s., Part I., 1916.

mass provided the material for the Ordovician sediment. These in many cases had to be transported over long distances, so that felspars would be rarely preserved—only those derived from close at hand would remain as clear grains.

This work was undertaken at the suggestion of Professor E. W. Skeats, in order to attempt an examination of the Ordovician sediments as W. G. Langford[7] had done of the Silurian. In order to bring the two works on to a comparative descriptive basis, the writer has set his work out on as similar lines to those of Langford as space would allow.

Mineralogically, W. G. Langford's inference that the Ordovician and Silurian would contain somewhat similar constituents[8] is borne out, but it may be noted that the occurrence of strain polarisation in the quartz grains is not by any means common as Langford inferred may be the case. It is perhaps possible that the Melbourne Silurian sediments have been derived from an area where the Ordovician has been subjected to even still greater compressive forces than in the Bendigo area. Mineralogically, the only difference between the constituents of the two series appears to be the relative absence of sapphire and unaltered biotite in the Ordovician.

In conclusion the writer wishes to acknowledge his thanks to the Bendigo School of Mines' officials for the use of their assay laboratory; to Dr. F. L. Stillwell for the invaluable use of his rock sections; and to Professor E. W. Skeats and Dr. H. S. Summers for their occasional excellent advice.

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[7] Op. cit.

[8] Op. cit., page 49.